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GRADIOMETER-AIDED RAPID GRAVITY SURVEY SYSTEM.(U)
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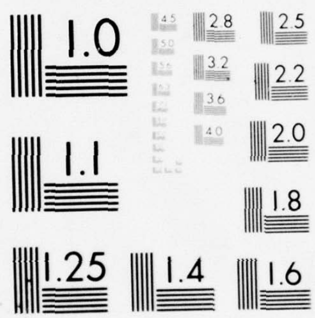
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GRADIOMETER-AIDED RAPID GRAVITY SURVEY SYSTEM

18 October 1976
Revised 22 April 1977

Prepared for:

U.S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES
Fort Belvoir, Virginia 22060

Submitted in fulfillment of
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THE ANALYTIC SCIENCES CORPORATION
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Rapid Gravity Survey System (RGSS)
Gradiometry
Zero Velocity
Kalman Processing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report considers a mobile vehicle equipped with both an inertial positioning system (IPS) and a gradiometer. For suitable gradiometer-aiding configurations, the following variables are determined: (1) Real-Time vs Post-Mission Data Processing, (2) Presence or absence of Terminal Calibration Data, (3) Continuous Time vs Halted Vehicle Gradiometer Operation, (4) Gradiometer Errors, (5) Zero Velocity and Gradiometer Calibration Stops, and (6) Gyro and accelerometer Errors. This report concluded that one sec or better gradiometer-aided

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20. continued

RGSS performance in open traverse is unlikely without vertical deflection end calibration. In addition, the keynote of successful RGSS/Gradiometer integration will be control and compensation of system bias and low frequency error sources.

FOREWORD

This document contains material used in a presentation given by The Analytic Sciences Corporation. The material is not intended to be self-explanatory, but rather should be considered in the context of the overall presentation.

OVERVIEW

R-25236

- RAPID GRAVITY SURVEY SYSTEM SCENARIO AND PERSPECTIVE ON GRADIOMETRY
- VERTICAL DEFLECTIONS FROM GRADIOMETER DATA ALONE
- GRADIOMETER-AIDED RGSS SIMULATION DESCRIPTION
- COVARIANCE SIMULATION RESULTS (FIRST PHASE)
- PRELIMINARY CONCLUSIONS AND A LOOK AHEAD

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RAPID GRAVITY SURVEY SYSTEM (RGSS)
SCENARIO AND PERSPECTIVE ON GRADIOMETRY

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PROBLEM STATEMENT

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CONSIDER A MOBILE VEHICLE EQUIPPED WITH BOTH AN INERTIAL POSITIONING SYSTEM (IPS)* AND A GRADIOMETER. FOR SUITABLE GRADIOMETER-AIDING CONFIGURATIONS, DETERMINE THE EFFECT OF THE FOLLOWING VARIABLES:

- REAL-TIME vs POST-MISSION DATA PROCESSING
- PRESENCE OR ABSENCE OF TERMINAL CALIBRATION DATA
- CONTINUOUS TIME vs HALTED VEHICLE GRADIOMETER OPERATION
- GRADIOMETER ERRORS
- ZERO VELOCITY AND GRADIOMETER CALIBRATION STOPS
- GYRO AND ACCELEROMETER ERRORS

*CURRENTLY CONFIGURED AS A LITTON LN15 INERTIAL NAVIGATION SYSTEM WITH IMPROVED (A-1000) VERTICAL CHANNEL ACCELEROMETER

REFERENCE: Huddle, J.R., "Navigation to Surveying Accuracy With an Inertial System," Bicentennial National Aerospace Symposium, Warminster, PA, April 1976.

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TYPICAL SURVEY CONFIGURATION

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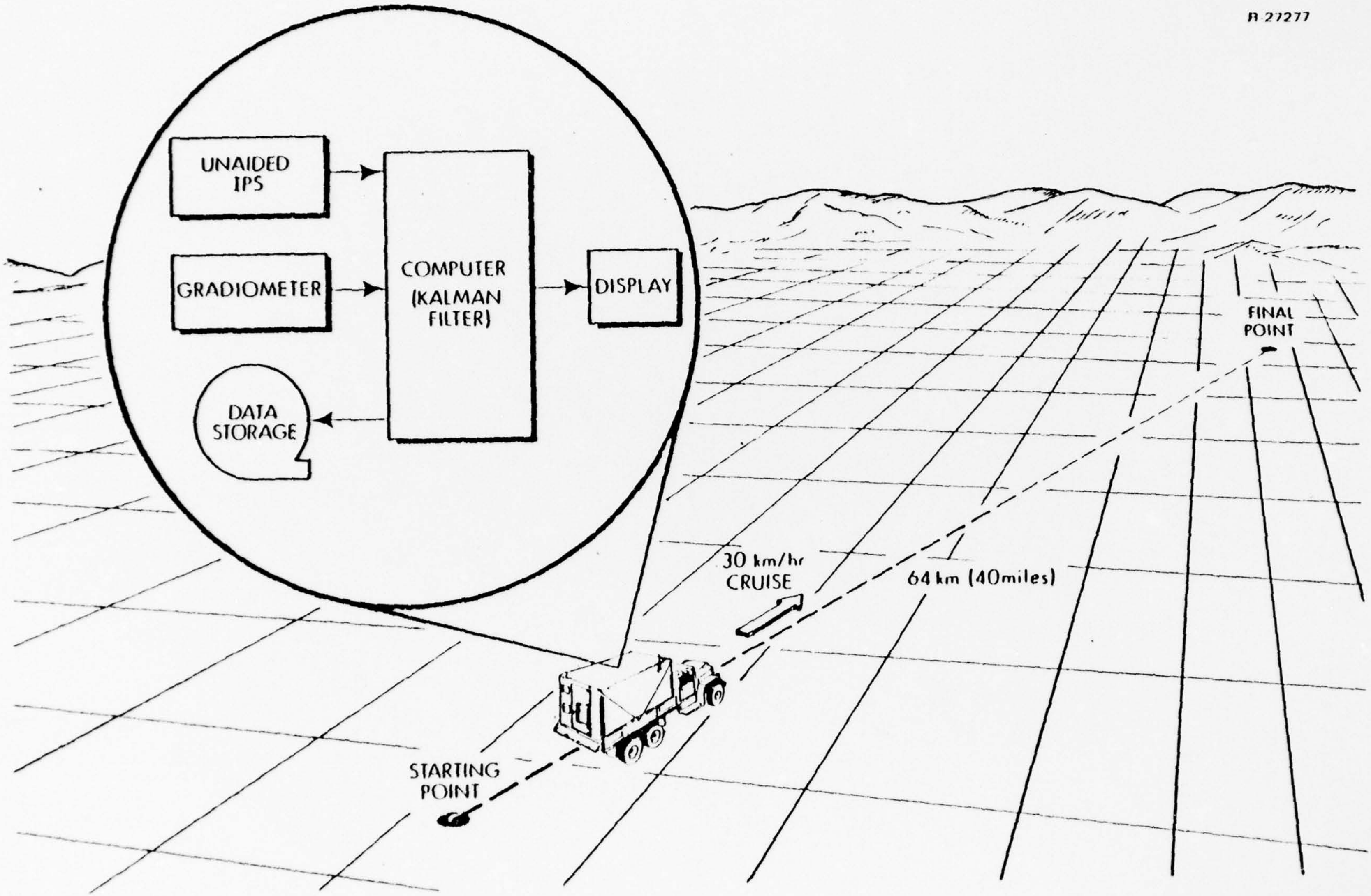

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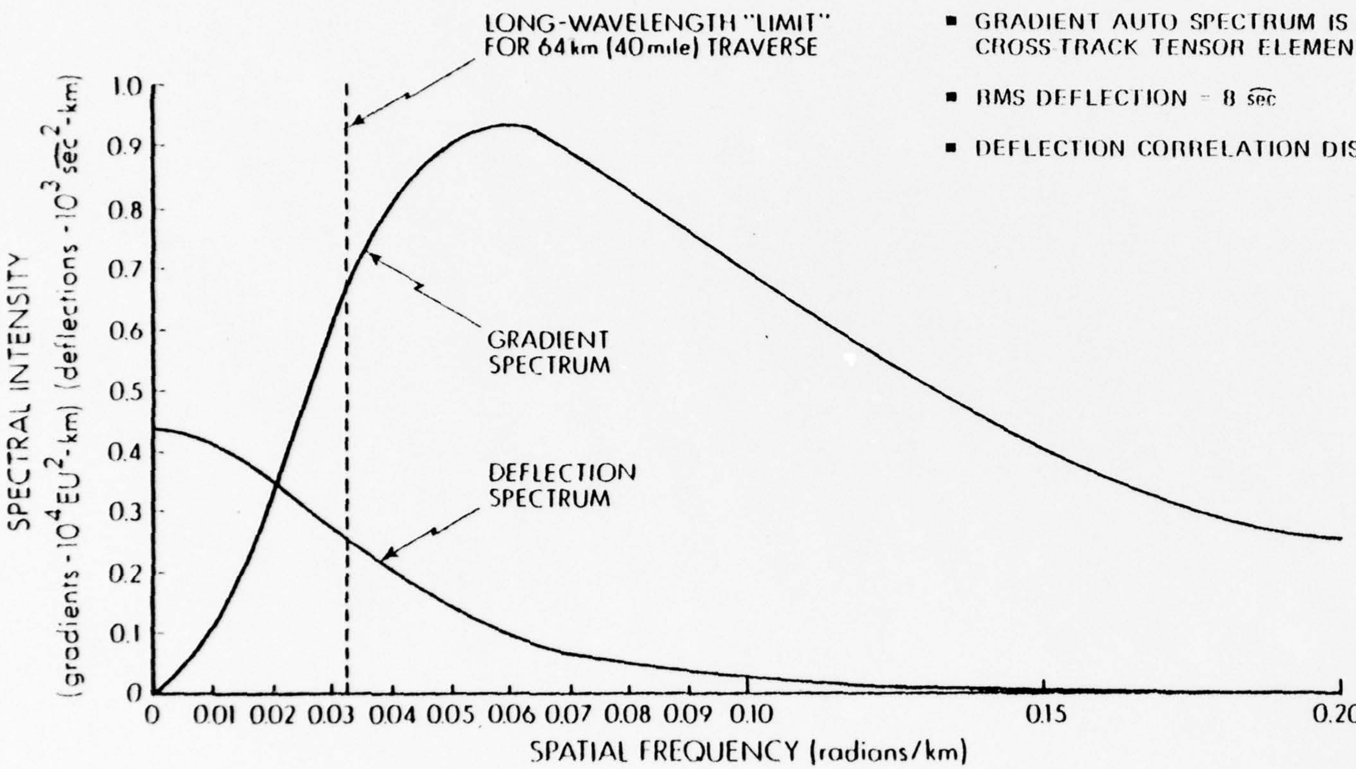
GRAVITY QUANTITY POWER SPECTRA

R 25274

- SECOND ORDER MARKOV CROSS-TRACK DEFLECTION MODEL
- GRADIENT AUTO SPECTRUM IS FOR ALONG-TRACK, CROSS-TRACK TENSOR ELEMENT
- RMS DEFLECTION = 8 $\widehat{sec}$
- DEFLECTION CORRELATION DISTANCE = 37 km



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MULTISENSOR VIEW OF GRADIOMETER-AIDED RGSS

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- GRADIOMETER MEASURES SHORT WAVELENGTH FEATURES OF THE GRAVITY FIELD
- IPS MEASURES LONG WAVELENGTH FEATURES
- OPTIMAL COMBINATION OF BOTH SETS OF MEASUREMENTS (KALMAN FILTERING OR SMOOTHING) YIELDS BEST (IN A LEAST SQUARES SENSE) DEFLECTION RECOVERY

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VERTICAL DEFLECTIONS FROM GRADIOMETER DATA ALONE

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NON-MOBILE, GRADIOMETER-ALONE VERTICAL DEFLECTION SURVEY

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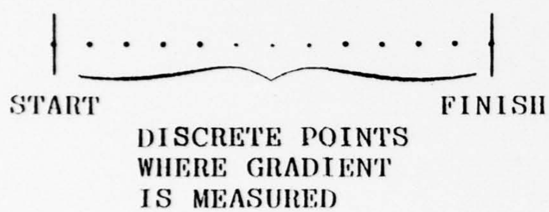

SAMPLE SPACING LIMITS VERY SHORT WAVELENGTH DEFLECTION RECOVERY

LENGTH OF TRAVERSE LIMITS LONG WAVELENGTH RECOVERY

- SIMPLEST IMAGINABLE GRADIOMETER SURVEY APPROACH
- DOES NOT TAKE ADVANTAGE OF LONG WAVELENGTH INFORMATION AVAILABLE FROM INERTIAL SYSTEM
- DEFLECTION RECOVERY RESULTS NOT LIMITED BY HIGH FREQUENCY GRADIOMETER ACCURACY

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VERTICAL DEFLECTION RECOVERY WITH DISCRETE, NON-MOBILE GRADIOMETER MEASUREMENTS ONLY

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NUMBER OF DISCRETE GRADIOMETER MEASUREMENTS (Equally Spaced)	GRADIOMETER NOISE		RMS DEFLECTION ESTIMATION ERROR FOR ENTIRE TRAVERSE ($\widehat{sec}$)
	WHITE (EU)*	BIAS (EU)	
10 (7.1 km spacing)	0	0	4.9
10 (7.1 km spacing)	1.0	0	5.4
10 (7.1 km spacing)	0	1.0	6.9
41 (1.6 km spacing)	1.0	0	4.3
41 (1.6 km spacing)	0	0	3.8

- RMS VERTICAL DEFLECTION = $8 \cdot \widehat{sec}$
- DEFLECTION CORRELATION DISTANCE = 37 km
- TRAVERSE DISTANCE = 64 km (40 mi)
- VEHICLE "DWELL TIME" AT EACH MEASUREMENT SITE = 100 seconds
- OPTIMAL POST-MISSION DATA PROCESSING (SMOOTHING)

CONCLUSION: GRADIOMETER MUST OPERATE IN MULTISENSOR CONTEXT

*TEN SECOND MOVING WINDOW AVERAGE

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GRADIOMETER-AIDED RGSS SIMULATION DESCRIPTION

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SIMULATION FEATURES

R-25244

- OPTIMAL KALMAN PROCESSING OF DATA
- ERROR COVARIANCE HISTORY OF RESIDUAL GRAVITY, VELOCITY AND POSITION ERRORS ALONG SURVEY TRACK
- SINGLE-CHANNEL, "QUICK-LOOK" ANALYSIS
- PROVISION FOR INCLUSION OF GYRO ERRORS
- PROVISION FOR ZERO VELOCITY UPDATES (VELOCITY AND GRADIOMETER "FIXES")
- GRADIOMETER OUTPUT SUPPRESSED DURING ACCELERATION AND DECELERATION

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MISSION PROFILE

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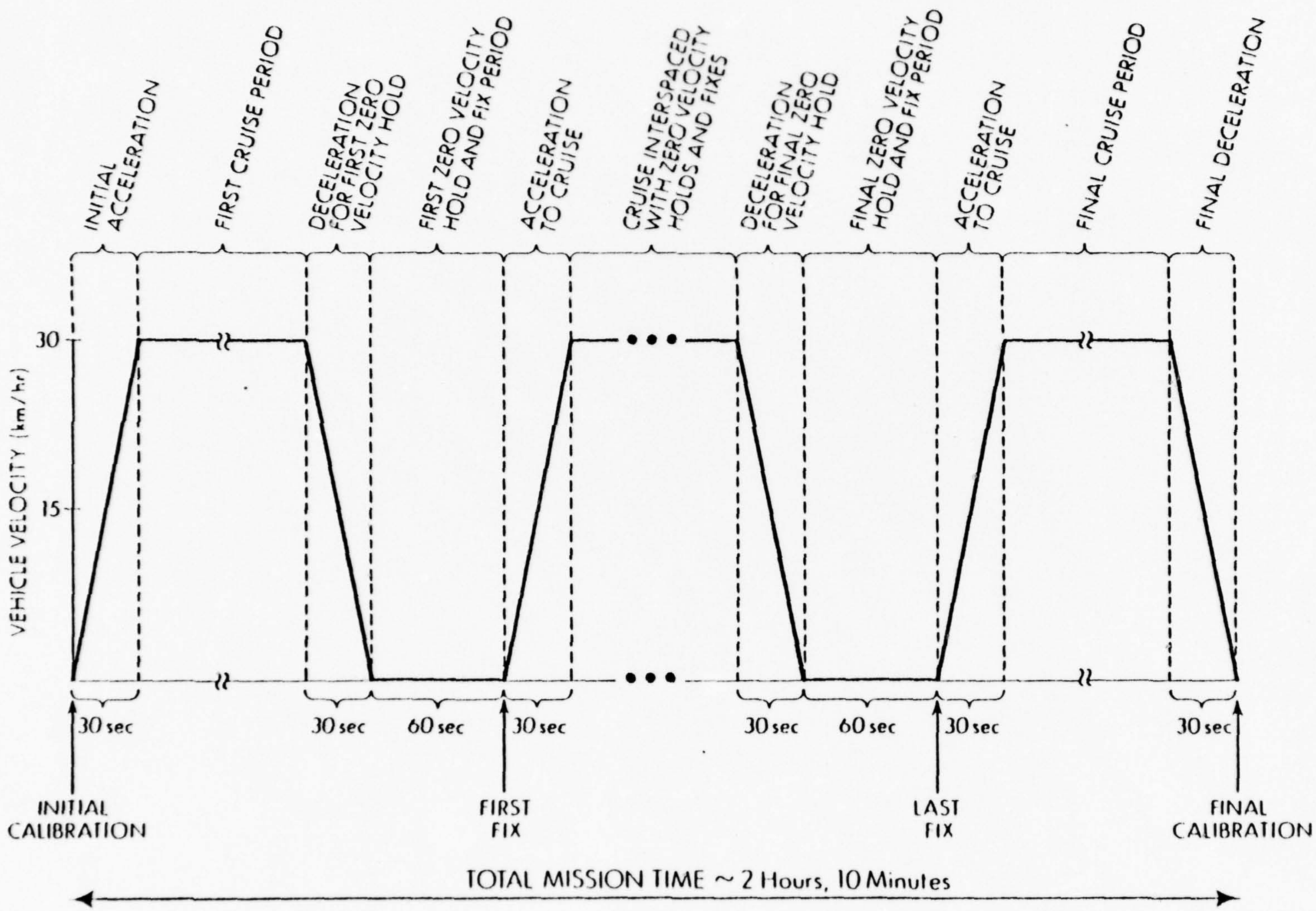

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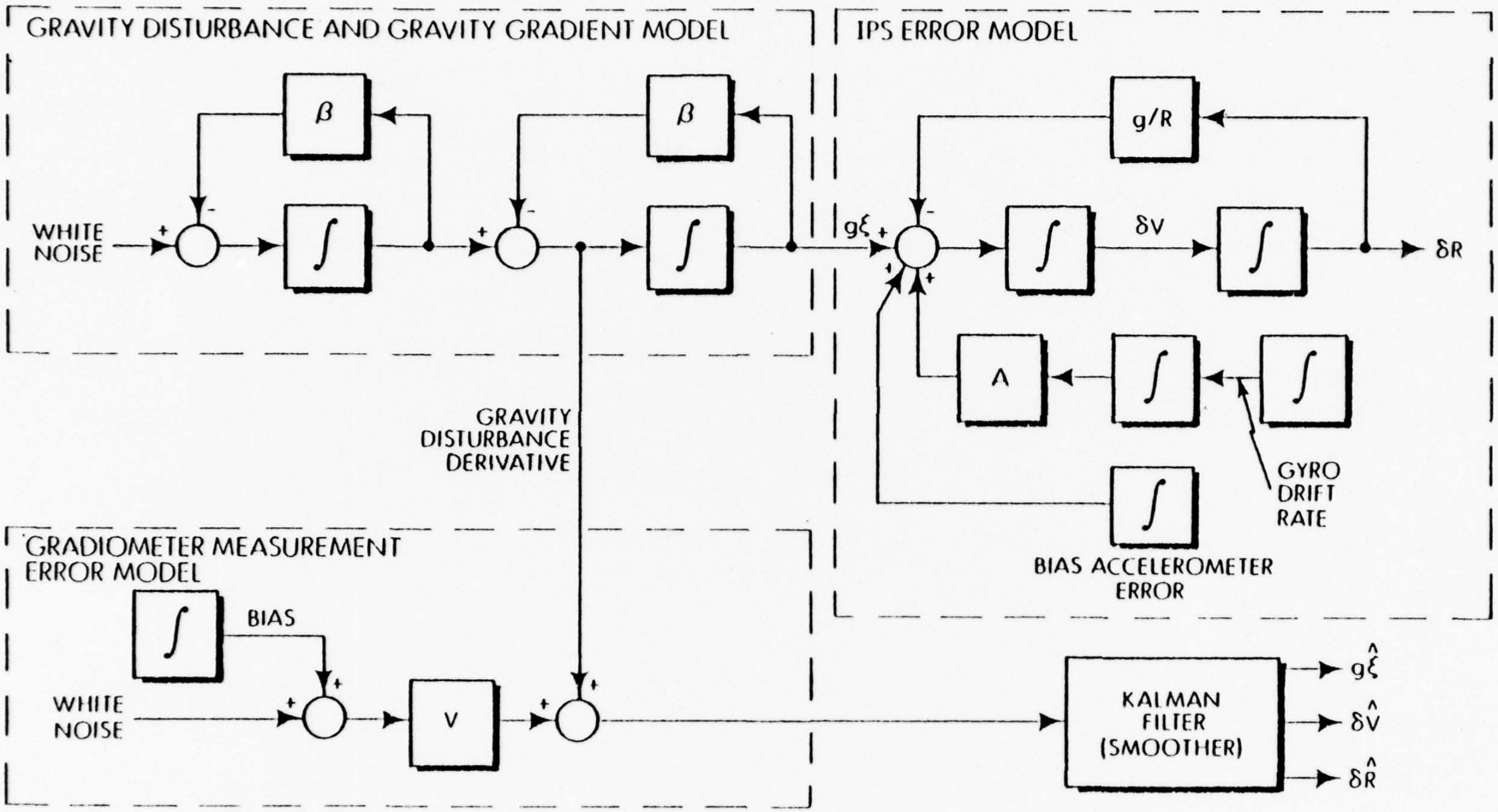
COVARIANCE SIMULATION MODEL FOR MOVING VEHICLE WITH MOBILE GRADIOMETER



V = ALONG-TRACK VELOCITY
A = ALONG-TRACK ACCELERATION
δV = CROSS-TRACK VELOCITY ERROR
δR = CROSS-TRACK POSITION ERROR
ξ = CROSS-TRACK VERTICAL DEFLECTION

β = DEFLECTION CORRELATION FREQUENCY
g = GRAVITY
R = EARTH RADIUS
^ = ESTIMATED QUANTITY

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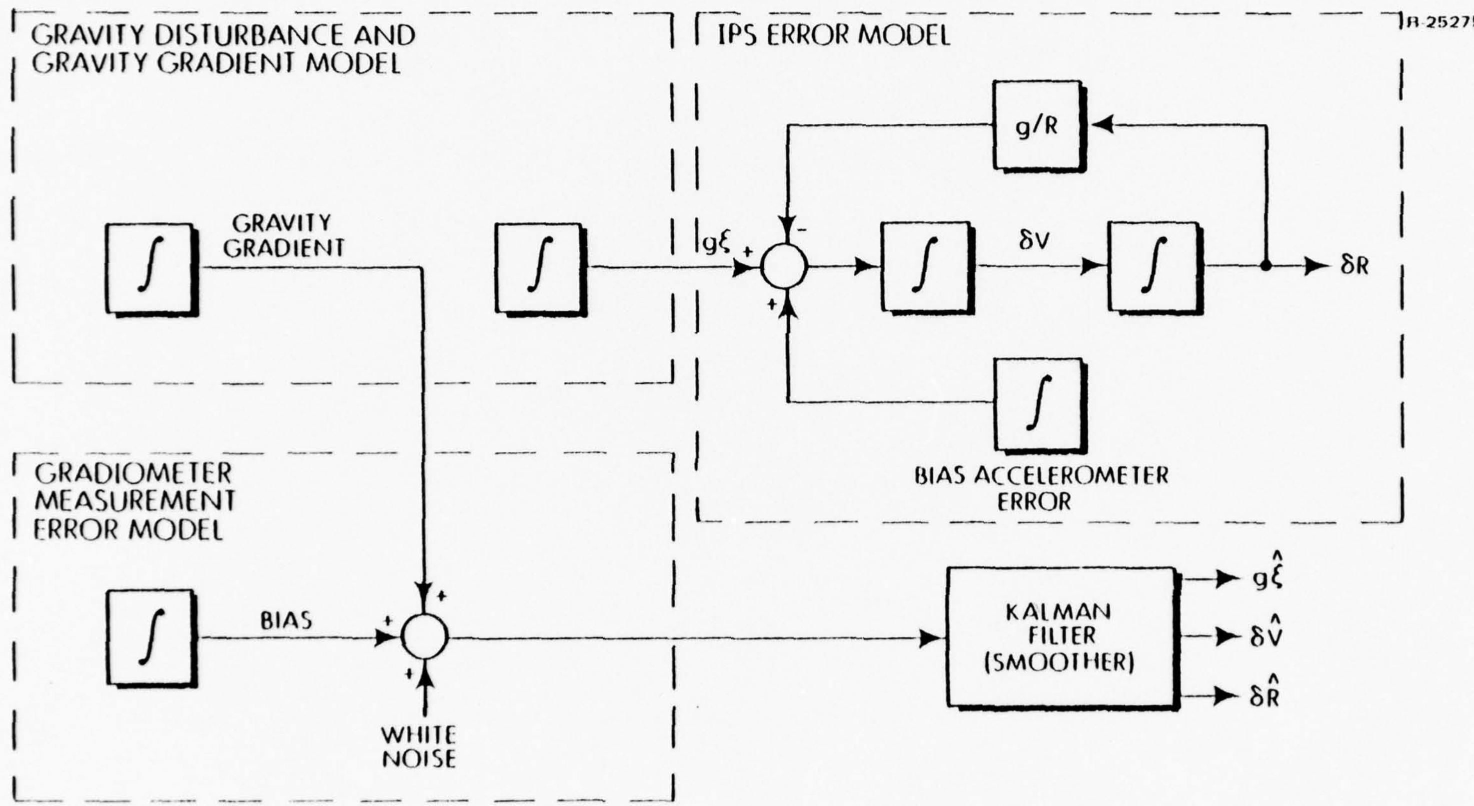
SIMULATION MODEL FOR STATIONARY VEHICLE AND GRADIOMETER



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SUMMARY OF SIMULATION CONSTANTS

R-25245a

<u>SURVEY</u>

TRAVERSE DISTANCE = 64 km (40 miles)
VEHICLE CRUISE SPEED = 30 km/hr
ACCELERATION PERIODS = 30 seconds each

<u>BACKGROUND GRAVITY DISTURBANCE FIELD (MARKOV)</u>

VERTICAL DEFLECTION = 8 $\widehat{sec}$ rms
DEFLECTION CORRELATION DISTANCE = 37 km

<u>SYSTEM FIELD CALIBRATION AND "FIXES"</u> (When Applicable)

TERMINAL POINT DWELL TIME = 1000 seconds
ZERO VELOCITY UPDATE DWELL TIME = 60 seconds

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SUMMARY OF SIMULATION VARIABLES
(FIRST PHASE SIMULATION RESULTS)

GRADIOMETER ERRORS

WHITE NOISE = 10 EU*

BIAS = 0, 10 EU

IPS ERRORS

RESIDUAL CROSS-TRACK ACCELEROMETER ERROR = 4 sec

VERTICAL COMPONENT OF POLAR GYRO DRIFT RATE = 0

CALIBRATION AND FIX TAKING

CALIBRATION QUANTITIES AT END POINTS - POSITION, VELOCITY, DEFLECTION, GRAVITY GRADIENT

NUMBER OF STOPS (VELOCITY AND GRADIENT FIXES) - 0

*TEN SECOND MOVING WINDOW AVERAGE

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COVARIANCE SIMULATION RESULTS
(FIRST PHASE)

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FIRST PHASE SIMULATION STUDY CASES

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RGSS DEFLECTION RECOVERY AND NAVIGATION ACCURACY WITHOUT GRADIOMETER-AIDING (REAL-TIME AND POST-MISSION)

CASE	QUANTITIES INCLUDED IN HIGH QUALITY ENDPOINT CALIBRATION
1	δR, δV
2	δR, δV, ξ
3	δR, δV, ξ, $\partial\xi/\partial x$*

RGSS DEFLECTION RECOVERY AND NAVIGATION ACCURACY WITH MOVING-BASE GRADIOMETER-AIDING (REAL-TIME AND POST-MISSION)

CASE	QUANTITIES INCLUDED IN HIGH QUALITY ENDPOINT CALIBRATION	GRADIOMETER ENDPOINT CALIBRATION† ASSUMED
4	δR, δV, ξ	NO
5	δR, δV	YES
6 (No bias errors)	δR, δV	NO

* $\partial\xi/\partial x$ = GRAVITY DISTURBANCE GRADIENT

† GRADIOMETER OUTPUT IS AVERAGED DURING 1000 SECOND CALIBRATION INTERVAL

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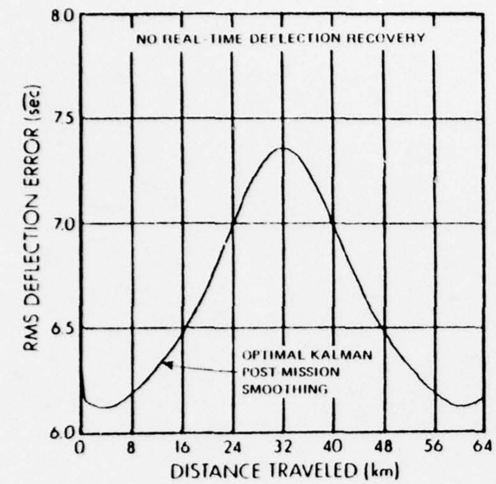
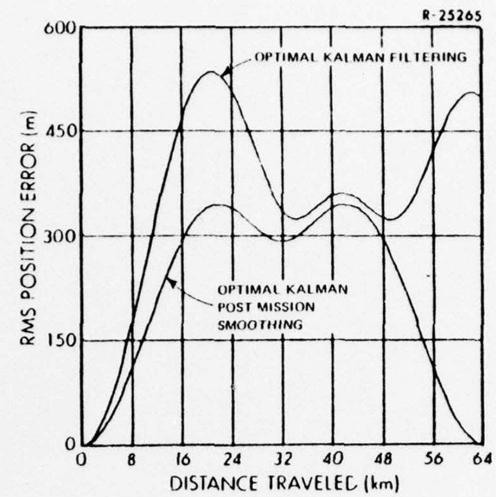
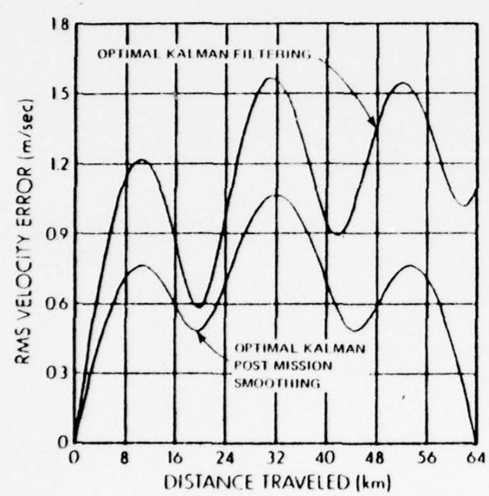
RGSS SURVEY ERRORS FOR OPTIMAL KALMAN PROCESSING OF ENDPOINT CALIBRATION DATA







CASE 1

- NO GRADIOMETER AIDING
- PRECISION ENDPOINT CALIBRATION OF
  - POSITION
  - VELOCITY

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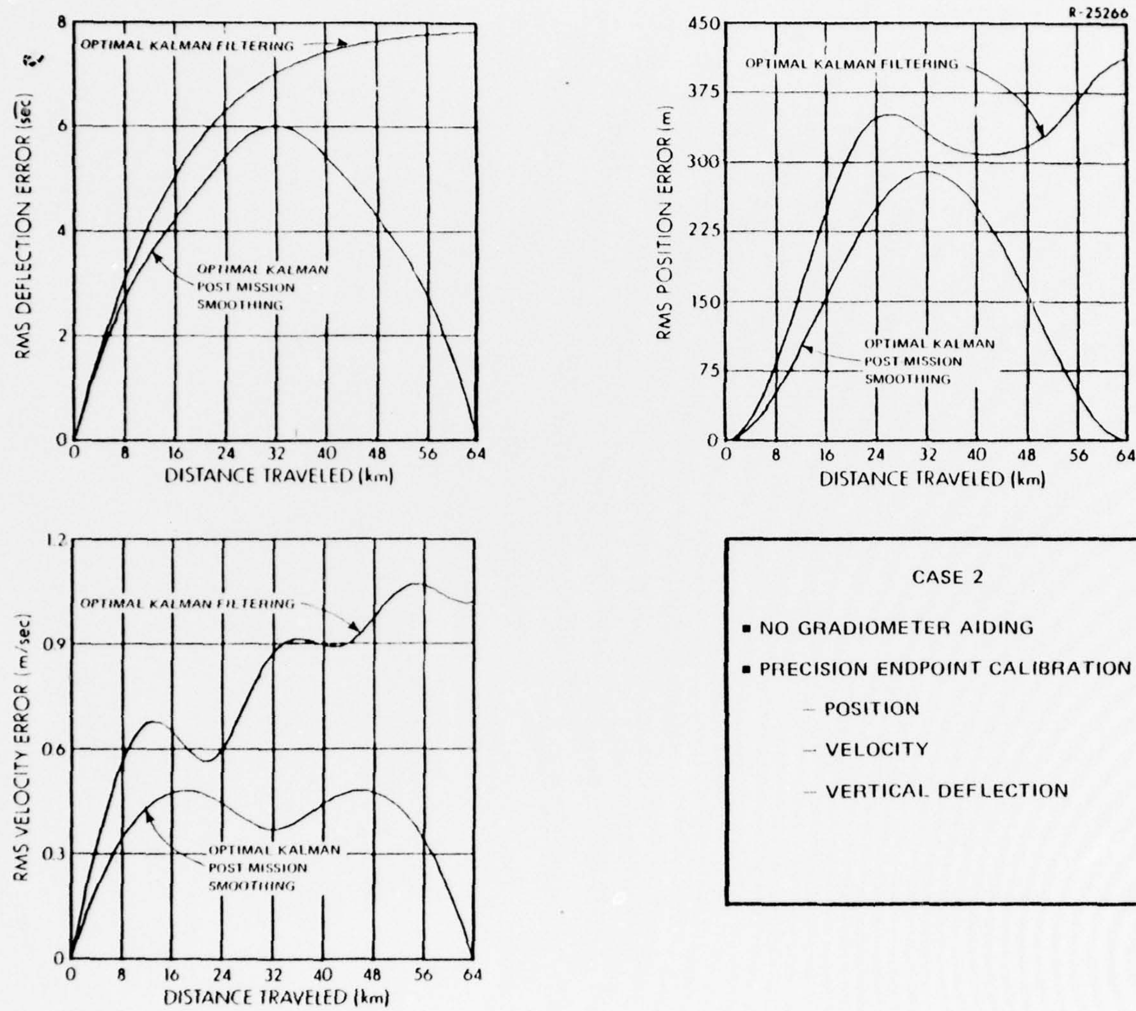
RGSS SURVEY ERRORS FOR OPTIMAL KALMAN PROCESSING OF ENDPOINT CALIBRATION DATA



CASE 2

- NO GRADIOMETER AIDING
- PRECISION ENDPOINT CALIBRATION OF
  - POSITION
  - VELOCITY
  - VERTICAL DEFLECTION

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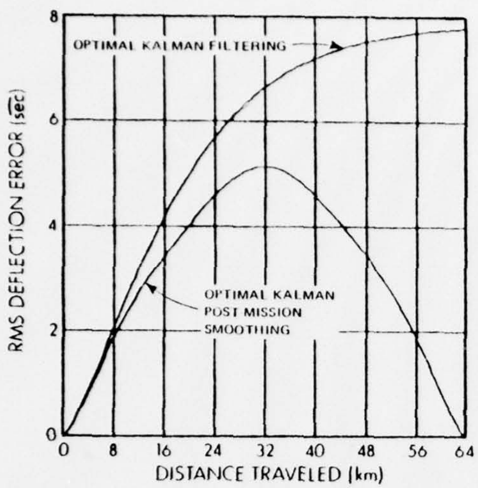
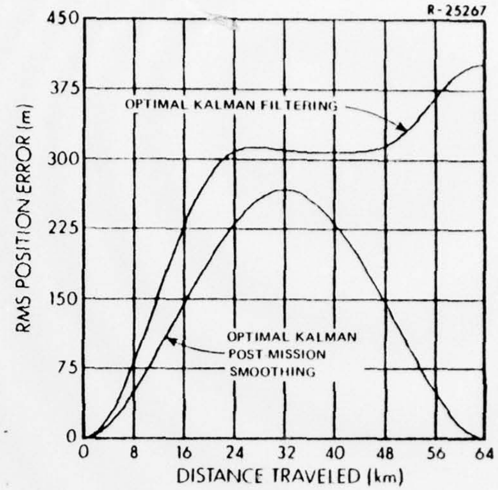
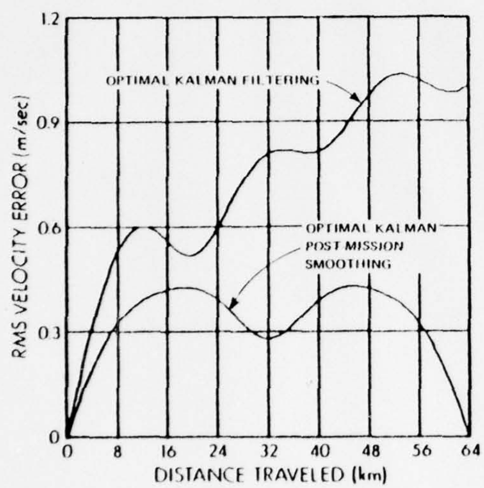
RGSS SURVEY ERRORS FOR
OPTIMAL KALMAN PROCESSING OF ENDPOINT CALIBRATION DATA







CASE 3

- NO GRADIOMETER AIDING
- PRECISION ENDPOINT CALIBRATION OF
  - POSITION
  - VELOCITY
  - VERTICAL DEFLECTION
  - GRAVITY GRADIENT

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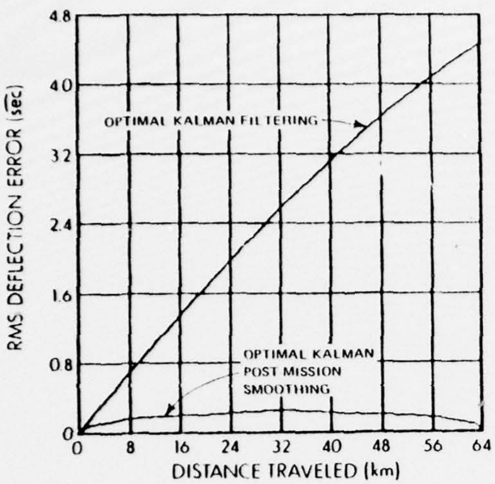
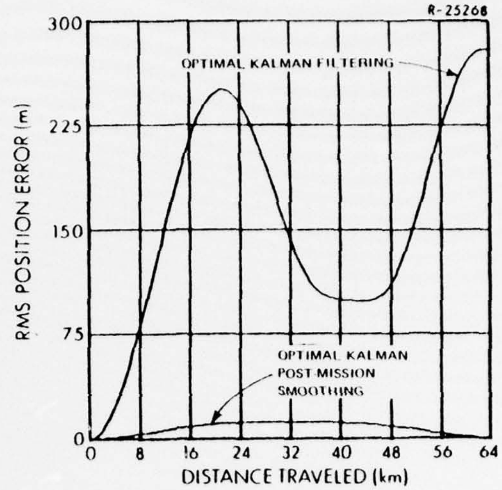
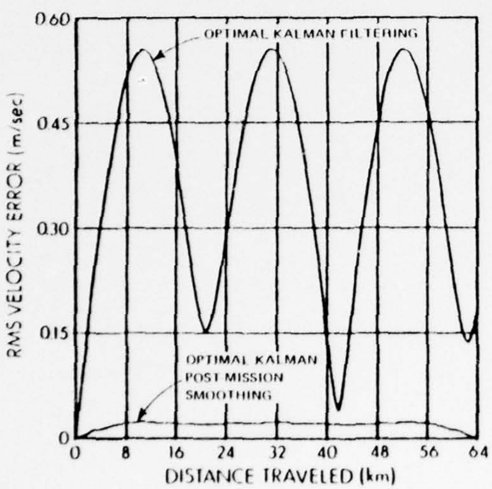
RGSS SURVEY ERRORS FOR OPTIMAL KALMAN PROCESSING OF GRADIOMETER AND ENDPOINT CALIBRATION DATA







CASE 4

- WITH MOVING-BASE GRADIOMETER AIDING
- PRECISION ENDPOINT CALIBRATION OF
  - POSITION
  - VELOCITY
  - VERTICAL DEFLECTION

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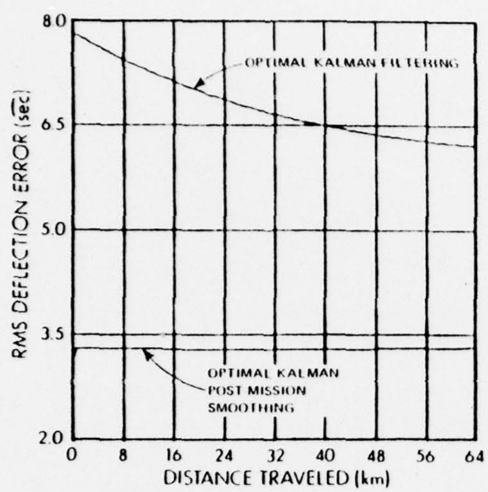
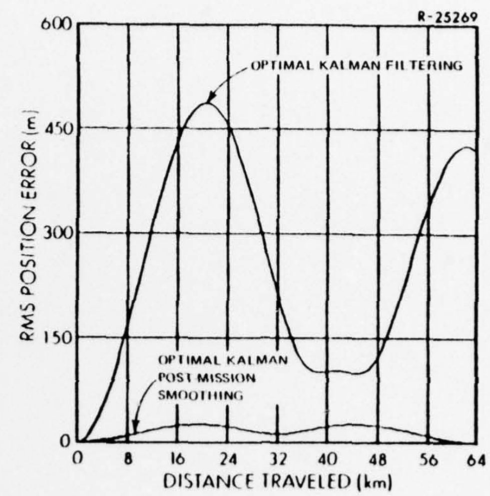
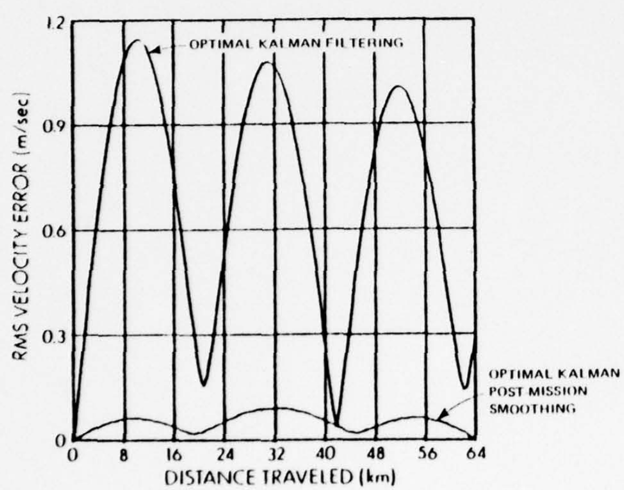
RGSS SURVEY ERRORS FOR OPTIMAL KALMAN PROCESSING OF GRADIOMETER AND ENDPOINT CALIBRATION DATA







CASE 5

- WITH MOVING-BASE GRADIOMETER AIDING
- PRECISION ENDPOINT CALIBRATION OF
  - POSITION
  - VELOCITY
- GRADIOMETER ENDPOINT CALIBRATION (1000 SECOND AVERAGE OF GRADIOMETER INSTRUMENT OUTPUT)

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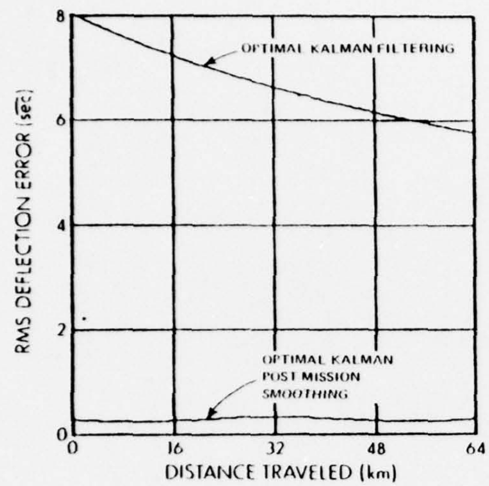
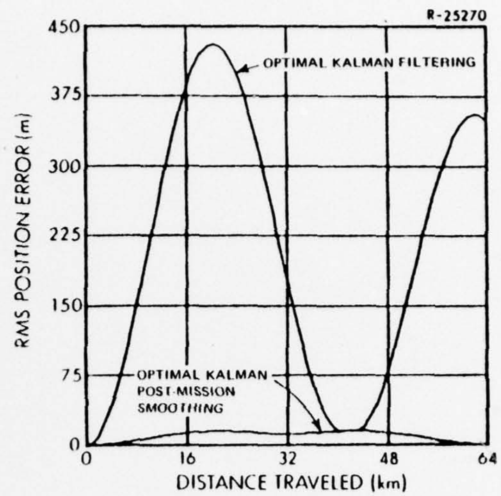
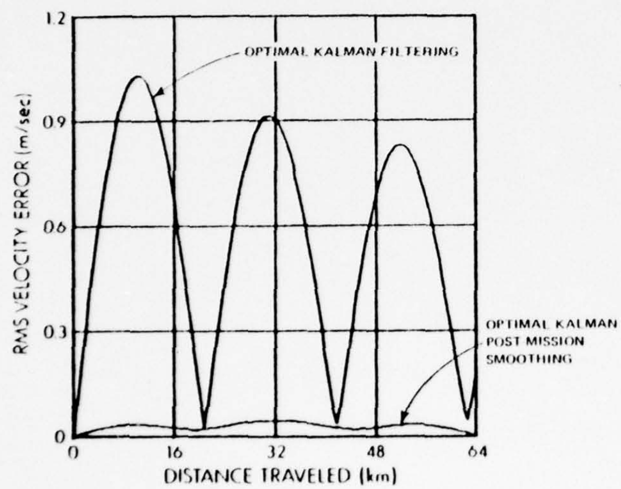
RGSS SURVEY ERRORS FOR OPTIMAL KALMAN PROCESSING OF GRADIOMETER AND ENDPOINT CALIBRATION DATA







CASE 6

- WITH MOVING-BASE GRADIOMETER AIDING
- PRECISION ENDPOINT CALIBRATION OF
  - POSITION
  - VELOCITY
- NO BIAS ACCELEROMETER ERROR
- NO BIAS GRADIOMETER ERROR

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SUMMARY OF SIMULATION RESULTS

CASE	TYPE OF END POINT CALIBRATION	GRADIOMETER ERRORS	RMS ERRORS OVER ENTIRE SURVEY					
			REAL-TIME OPTIMAL ESTIMATION			OPTIMAL SMOOTHING		
			DEFLECTION ($\widehat{sec}$)	POSITION (m)	VELOCITY (m/sec)	DEFLECTION ($\widehat{sec}$)	POSITION (m)	VELOCITY (m/sec)
1	$\delta R, \delta V$	NO GRADIOMETER	8.0	381	1.1	6.6	252	0.7
2	$\delta R, \delta V, \xi$	NO GRADIOMETER	6.4	299	0.8	4.3	181	0.4
3	$\delta R, \delta V, \xi, \frac{\partial \xi}{\partial x}$	NO GRADIOMETER	6.1	287	0.8	3.5	167	0.3
4	$\delta R, \delta V, \xi$	10 EU WHITE NOISE* AND 10 EU BIAS	$\boxed{2.8}$	174	0.4	$\boxed{0.2}$	$\boxed{8.3}$	0.02
5	$\delta R, \delta V, \left.\frac{\partial \xi}{\partial x}\right\vert$ FROM GRADIOMETER	10 EU WHITE NOISE* AND 10 EU BIAS	6.8	295	0.8	3.3	17.5	0.05
6†	$\delta R, \delta V$	10 EU WHITE NOISE* ONLY	6.8	254	0.6	0.3	10.7	0.03

* 10 SECOND MOVING WINDOW AVERAGE

† NOMINAL 4 $\widehat{sec}$ BIAS ACCELEROMETER ERROR SET TO ZERO

OBSERVATIONS

- PERFORMANCE OF MOBILE GRADIOMETER-AIDED RGSS VERY SENSITIVE TO ACCURACY OF TERMINAL DEFLECTION CALIBRATION

- VELOCITY AND GRAVITY GRADIENT FIXES ASSOCIATED WITH PERIODIC ZERO VELOCITY HOLDS EXPECTED TO PROVIDE SIGNIFICANT REDUCTION IN POSITION AND VELOCITY ERRORS; SMALL REDUCTION IN DEFLECTION ERRORS

- SIMILAR LOW FREQUENCY DYNAMICS OF DEFLECTIONS AND LOW FREQUENCY SYSTEM ERRORS CAUSE STRONG SENSITIVITY OF ESTIMATION ERROR TO BIAS-LIKE ERROR SOURCES

PRELIMINARY CONCLUSIONS AND A LOOK AHEAD

PRELIMINARY CONCLUSIONS

R-25262

ONE $\widehat{sec}$ OR BETTER GRADIOMETER-AIDED RGSS PERFORMANCE IN OPEN TRAVERSE IS UNLIKELY WITHOUT VERTICAL DEFLECTION END CALIBRATION

KEYNOTE OF SUCCESSFUL RGSS/GRADIOMETER INTEGRATION WILL BE CONTROL AND COMPENSATION OF SYSTEM BIAS AND LOW FREQUENCY ERROR SOURCES

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A LOOK AHEAD

R-25251

CURRENT AND SOON-TO-BE-DEVELOPED SIMULATION SOFTWARE WILL PROVIDE A FIRST-LOOK UNDERSTANDING OF THE FOLLOWING EFFECTS

- ULTIMATE PERFORMANCE POSSIBLE WITH RGSS OPTIMALLY AIDED BY NON-MOBILE GRADIOMETER
- RGSS PERFORMANCE IMPROVEMENT WITH ZERO-VELOCITY HOLDS (FIXES) IN ADDITION TO MOVING-BASE GRADIOMETER-AIDING
- DEGRADATION DUE TO INSTRUMENT ERRORS
  - DIFFERENT GRADIOMETER NOISE LEVELS
  - GYRO DRIFT
- INSIGHT INTO DEGRADATION DUE TO IPS ERRORS NOT OBSERVABLE AT ZERO-VELOCITY (e.g., ACCELEROMETER SCALE FACTOR)

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